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Knowledge to Go Places

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10-17-06

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Dear Dr. Ullal:

This is the third quarterly report of phase II of our research under the current Thin Film Partnership Program (Subcontract No. XXL-5-44205-02 to Colorado State University). A brief summary and details of our work are given below. This report is in fulfillment of deliverable D.2.3 of the subcontract statement of work (SOW).

Summary

During this quarter, we have progressed on the tasks outlined in our SOW for Phase II. Significant advances to the design of module packaging have been made. Desiccant containing materials for the edge seal and sealing of the holes in the back glass have been tested in damp heat tests at NREL with very promising results. Hardware modifications to the pilot system for automated cooling of the substrate in vacuum have been completed and device efficiencies of 11.83 % have been made in "all forward" process. Significant progress has been made in characterizing films with ellipsometry and the use of ellipsometry for quality control is being investigated. Efforts to improve device efficiency and advance device characterization are underway. Based on our current progress, no difficulties are anticipated in successfully completing the future targets outlined in the SOW.

A prototype production system to process 16.5x16.5 inch substrates continues to be advanced. This activity is supported by another program from DOE-EERE and cost shared by National Starch and Chemicals (NSC). As members of AVA technologies, our group has submitted a proposal to the DOE-SAI program. The participants in the project include: PPG Industries, NSC, CSU (three groups) and NREL.

Detailed Description of the Results:

1.Testing desiccant containing polymers for packaging:

Initially the design of the packaging for our modules will utilize glass/EVA/glass packaging. In order to reduce moisture ingress into the device, polymers with desiccants will be used for sealing the edges and also the holes in the back glass. Fixtures simulating the package design with the desiccant containing materials have been fabricated and are being tested at NREL under damp heat (85/85). A small quantity of moisture indicating material placed inside the fixture has not changed color after 1000+ hours of testing for the fixtures simulating the edge seal. The fixtures without the desiccant containing materials have failed (the moisture indicating material inside the fixture has changed color). The tests are continuing. This result is very promising. An advanced method for encapsulation has also been developed by NSC (reported in the last quarterly report). This method is also being developed in parallel.

2. Hardware Modifications

The pilot system for processing 3.6 x 3.1 inch substrates has been modified to more closely simulate the back contact processing suitable for actual industrial manufacturing. A fixture for automated cooling of the substrate in vacuum has been designed, fabricated, installed and tested. This fixture had water cooling only on the top part. During this quarter, water cooling was also added to the bottom part of the fixture. This was found to be necessary since the bottom part was getting hot from the adjacent sources. As discussed in our earlier reports, this is needed for optimum processing of the back contact. The cooling of the substrates during processing was measured by IR detectors. A journal article has been drafted on the in-situ cooling approach and has been submitted to Journal of vacuum Science and Technology. A patent application has also been filed. Device efficiencies of 11.83% have been obtained with an "all forward" process (pl. see our earlier reports for discussions of the "all forward" process). **It is noted that the total time for processing the 11.83% device is only 22 minutes.** This includes glass heating, CdS deposition, CdTe deposition, CdCl2 treatment and back contact processing.

3. Higher Efficiency

We have demonstrated NREL verified efficiencies of 12.44% on unmodified Pilkington TEC15 glass. In order to obtain higher efficiencies, low iron sodalime (white glass) glass plates with TO:F applied by APCVD have been received from Sierratherm. The coated substrates have been studied and the results are shown in Figure 1 below.

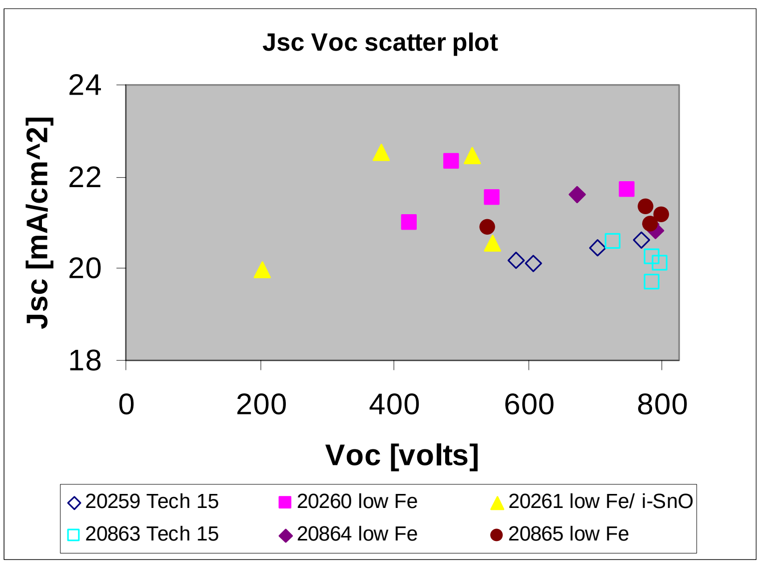

Figure 1: Jsc Voc scatter plot of devices with thinner CdS on three different substrates

Three different substrates have been investigated for higher efficiency. These are: TEC15, Low Fe, and Low Fe with i-SnOx coating. The i-SnOx coatings were provided by Chris Ferekides of

USF. Our current standard process produces Jsc of 20 mA/sq. cm. at ~800mV.(open blue squares have slightly smaller CdS thickness compared to the standard). When the CdS thickness was reduced, an increase in Jsc was observed, but the Voc decreased. Nearly 100 substrates and 24 devices were part of the thin CdS study. Six devices have been provided to Prof. Sites' group for LBIC and QE studies.

Further optimization of the TCO and CdS will be needed for obtaining higher efficiencies. Four 3 X 3 inch. Low Fe substrates with ITO/i-SnOx coating are being provided by Chris Ferekides of USF. Xuanzhi Wu of NREL has supplied four 3 X 3 inch LOF TEC 15 substrates with a ZTO buffer layer. These substrates will be used for future efforts to increase device efficiency.

<u>4. Device Characterization Studies:</u>

Spectroscopic ellipsometry is being investigated as a quality control tool. It is hoped that ellipsometry would provide a nondestructive means of measuring thickness uniformity of CdS/CdTe films on large areas. It is also possible that by tracking optical constants measured by ellipsometry it would be possible to correlate this data to process variation. Efforts are underway to qualify the technique and verify its usefulness.

In order for ellipsometry to predict layer thicknesses and optical constants for a multi-film stack an analytical model must be developed. Sandeep Kohli of the CSU central instrumentation facility has used a J. A. Woollam Vase ellipsometer to collect experimental spectrums from several samples processed in our laboratory. Working in collaboration with the Woollam Co. Sandeep constructed an analytical model to predict the optical constants and layer thicknesses for the measured samples. The model fit to the experimental data for a representative sample is shown in Figure 2. The model has 14 layers and the mean squared error for this fit is 24.22, which is considered to be a good fit.

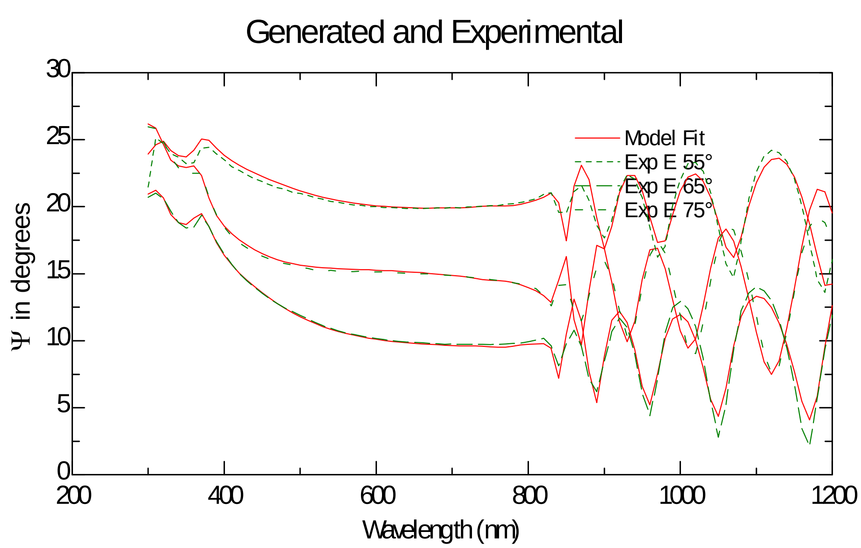

Figure 2: Spectroscopic ellipsometry data and model fit for a LOF Tec 15 substrate with SnO:F/CdS/CdTe:Cu which had received $CdCl_2$ treatment.

The most difficult part of developing the analytical model was to obtain a good fit to the glass/SnOx substrate. Sandeep eventually used 6 layers including one layer with graded optical constants to fit the measured data. Initial profilometry measurements of the CdS/CdTe layer thickness match the CdS/CdTe thickness predicted by the model. Cross sectional SEM characterization of the samples is also underway to verify the ellipsometry data.

At this point a reasonable model has been obtained and now the predictive capability of the model must be further verified. Optimization and further development of the model will also be pursued. Al Enzenroth of the CSU Materials Engineering Laboratory attended a four day spectroscopic ellipsometry short course on data analysis presented by the Woolam Co. at Arizona State University. In order to exercise the model more samples with varied film thicknesses will be fabricated. Ellipsometry data will be obtained from these samples and the model predictions will be checked. Multiple ellipsometry measurements on 3 in. X 3 in. samples will also be performed to measure uniformity.

Collaboration is continuing with Fred Seymour at the Colorado School of Mines. Fred performed admittance spectroscopy measurements on several cells fabricated at the CSU MEL. These cells included poor $CdCl_2$ without Cu and good $CdCl_2$ with and without Cu. A brief summary of the results follows. For poor $CdCl_2$ without Cu there was a uniform spatial distribution of deep states with an activation energy of 0.320 eV. For a cell with good $CdCl_2$ treatment there was a uniform spatial distribution of deep states with an activation energy of 0.130 eV. This deep state may be assigned to the Cl A-center complex or other states related to Cl. The addition of Cu to a cell with a good $CdCl_2$ treatment introduces a deep state at 0.350 eV. This deep state has a relatively high density and a non-uniform spatial distribution. The decrease in capacitance signal with increasing temperature indicates a steep concentration gradient near the back contact. This deep state may be assigned to Cu_{Cd}. In all three cells there was evidence of deep states with a continuous energy band with activation energies deep in the band gap. The concentration of this distributed band was lowest for the cell with good $CdCl_2$ with Cu.

5. Collaborative Studies with NREL:

Our group has developed a technique for defining CdTe cell areas on glass substrates. The technique consists of applying a contact mask and removal of unmasked areas with an abrasive blast. Xuanzhi Wu supplied four CdTe substrates for initial testing of the abrasive blast technique on NREL devices. Circular areas of ~ 0.69 cm^2 were defined and the cells were returned to NREL for evaluation. These devices performed well when studied under IR camera. Additional substrates for cell definition have been received from NREL. In order for NREL to develop this capability internally, detailed guidance on the method and hardware was provided to Dave Albin of NREL and the blaster and the media were specified. Three samples at various stages of processing have been provided to Helio Moutinho of NREL for studies with atomic force microscopy.

6. Collaborative Studies and Other Activities:

During this quarter, the following collaborative activities were conducted:

1) Brian Murphy, Fred Seymour and Russell Black of Primestar Solar were given a detailed tour of the lab. and many insights on the effect of processing on device stability were discussed.
2) Our laboratory was part of an organized self guided tour of the American Solar Energy Society. Nearly 100 visitors visited the laboratory over a six hour period.
3) Mani Manivannan from the Global Research Center of GE has joined our department and is continuing his research on CdTe photovoltaics. He is participating in the SAI proposal

mentioned earlier. He visited NREL with Al Enzenroth from our group to discuss collaboration under the SAI program.

7. Update on outdoor testing:

Eleven optimally processed devices are being tested outdoors under open circuit conditions. These devices were recently measured and the results are shown below in Figure 3. It is noted that most of the devices have maintained an efficiency of 10% after nearly 5 years outdoors at open circuit conditions. Accelerations factors of 7 to 100 have been reported in the literature for CdTe devices between open circuit and max. power condition.

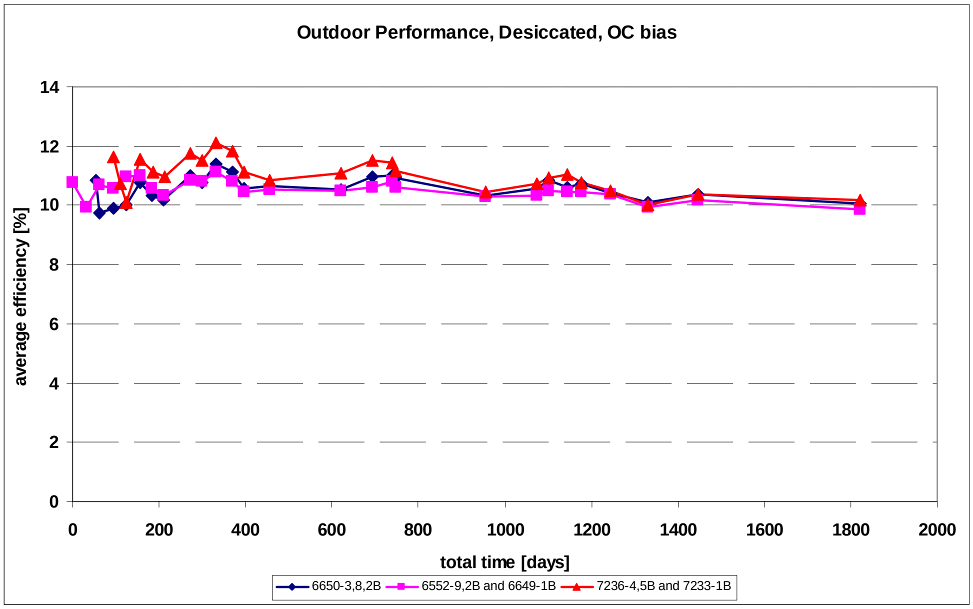

Figure 3: Average efficiency versus time for groups of cells in outdoor test conditions

If you have any questions, please do not hesitate to call the laboratory at (970)-491-8411. Thank you.

Sincerely,

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CC: C. Lopez